

Redshifted H I and OH absorption in radio galaxies and quasars

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ABSTRACT

From a survey for redshifted H I 21-cm and OH 18-cm absorption in the hosts of a sample of radio galaxies and quasars, we detect H I in three of the ten and OH in none of the fourteen sources for which useful data were obtained. As expected from our recent result, all of the 21-cm detections occur in sources with ultra-violet continuum luminosities of $L_{UV} \leq 10^{23} \text{ W Hz}^{-1}$. At these “moderate” luminosities, we also obtain four non-detections, although, as confirmed by the equipartition of detections between the type-1 and type-2 objects, this near-50% detection rate cannot be attributed to unified schemes of active galactic nuclei (AGN). All of our detections are at redshifts of $z \lesssim 0.67$, which, in conjunction with our faint source selection, biases against UV luminous objects. The importance of ultra-violet luminosity (over AGN type) in the detection of 21-cm is further supported by the non-detections in the two high redshift ($z \sim 3.6 - 3.8$) radio galaxies, which are both type-2 objects, while having $L_{UV} > 10^{23} \text{ W Hz}^{-1}$. Our 21-cm detections in combination with those previously published, give a total of eight (associated and intervening) H I absorbing sources searched and undetected in OH. Using the detected 21-cm line strengths to normalise the limits, we find that only two of these eight may have been searched sufficiently deeply in OH, although even these are marginal.

Key words: galaxies: active – quasars: absorption lines – radio lines: galaxies – ultra violet: galaxies – galaxies: fundamental parameters – galaxies: high redshift

1 INTRODUCTION

Although opaque to optical light, the dusty Universe is transparent to radiation at radio wavelengths, thus making the spectroscopic study of the 21-cm spin-flip transition of neutral hydrogen (H I) a very useful tool in probing the far reaches of the cosmos. The low probability of the transition compounded by the inverse square law, renders H I 21-cm currently undetectable in emission at redshifts of $z \gtrsim 0.1$. However, in the absorption of radio waves emitted from background quasars, the line strength depends only upon the column density of the absorber and the flux of the background source. Therefore by using absorption lines, we can in principal probe H I to redshifts of $z \sim 50$ (or when the Universe was 1% its present

age), where the ionosphere begins to affect low frequency radio waves ($\lesssim 30 \text{ MHz}$). With such observations we can address several outstanding questions in cosmology and fundamental physics:

- (i) Probe the Epoch of Re-ionisation – when the first ever stars ignited, re-ionising the gas in the smaller cosmos (e.g. Carilli et al. 2004).
- (ii) Determine the contribution of the neutral gas content to the mass density of the Universe (Kanekar et al. 2009; Curran 2010).
- (iii) Measure any putative variations in the values of the fundamental constants of nature at large look-back times, to at least an order of magnitude the sensitivity provided by the best optical data (see Tzanavaris et al. 2007). This offers one of the few experimental tests of current Grand Unified Theories, thus having profound implications for modern physics.

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This latter point requires the comparison of the redshift of the 21-cm line with other transitions, which may be optical/ultra-violet [from singly-ionised metals, giving $\Delta(\mu\alpha^2 g_p)/\mu\alpha^2 g_p$, where α is the fine structure constant, μ the electron-to-proton mass ratio and g_p the proton g-factor, millimetre-wave [rotational transition of molecules, giving $\Delta(\alpha^2 g_p)/\alpha^2 g_p$] or other decimetre transitions (see Curran et al. 2004a and references therein). Specifically, transitions arising from the hydroxyl radical (OH), which can also be intra-compared (Darling 2003), thus avoiding possible line-of-sight effects which could mimic a change in the constants.

Thus, highly redshifted H I 21-cm and OH 18-cm absorbers are of great interest, although these are currently very rare, with only 73 H I 21-cm absorption systems at $z \geq 0.1$ known – 41 of which occur in galaxies intervening the sight-lines to more distant quasars (see table 1 of Curran 2010), with the remainder arising in the host galaxies of the quasars themselves (see table 1 of Curran & Whiting 2010). In the case of OH, the situation is more dire with only five absorbers currently known (Chengalur et al. 1999; Kanekar & Chengalur 2002; Kanekar et al. 2003, 2005). Four of these were originally found through millimetre-wave molecular absorption, although further surveys have proven fruitless (see Curran et al. 2004b), which we suggest is due to the traditional optical selection of the sources: The target of choice in many previous surveys have been damped Lyman- α absorption systems (DLAs), since these are known to contain large columns of neutral hydrogen ($N_{\text{HI}} \geq 2 \times 10^{20} \text{ cm}^{-2}$, by definition) at precisely determined redshifts. Although 19 DLAs have been detected in the H₂ Lyman and Werner UV bands (see Noterdaeme et al. 2008; Jorgenson et al. 2009 and Srianand et al. 2010), these are at molecular fractions well below the detection thresholds of current microwave instruments (Curran et al. 2004b). Furthermore, the molecular abundances appear to be correlated with the colour of the background quasar in that the DLAs have molecular fractions of $\mathcal{F} \equiv \frac{2N_{\text{H}_2}}{2N_{\text{H}_2} + N_{\text{HI}}} \sim 10^{-7} - 0.3$ and $V - K \lesssim 4$, whereas the millimetre (and OH) absorbers have molecular fractions $\mathcal{F} \approx 0.6 - 1$ and optical-near-infrared colours of $V - K \gtrsim 5$ (see figure 3 of Curran et al. 2010b). That is, not only are the radio-band absorbers redder than those of the optical-band, but there may be a correlation between the normalised OH line strength and optical-near infrared colour (Curran et al. 2006), although this requires a larger number of detections for confirmation.

These points strongly suggest that the quasar light is reddened by the dust in the foreground absorber, which prevents the dissociation of the molecules by the ambient UV field. From this it is apparent that in order to detect redshifted molecular absorption with current radio instruments, targets must be selected on the basis of their optical and near-IR photometry, where we select the reddest objects. However, the obscuration responsible for the quasar reddening could be located anywhere between us and the quasar redshift (the three intervening systems are the strongest absorbers, see Sect. 4.2) and, although wide-band decimetre scans are more efficient than at millimetre wavelengths (Murphy et al. 2003; Curran et al. 2005), these are very susceptible to radio frequency interference (RFI). Therefore, in addition to our programme of using the wide-band spectrometer on the Green Bank Telescope (GBT) to perform 200 MHz wide frequency scans of the entire redshift space towards very red, radio-loud objects (see Curran et al. 2007), we are searching for H I and OH absorption associated with the host galaxy of the quasar. Here we add the results of our recently completed searches for associated absorption and discuss these in the context of our previous search results (Curran et al. 2006, 2008).

2 OBSERVATIONS

2.1 Sample selection

We observed five sources with the Effelsberg telescope and eleven with the Green Bank Telescope (with two sources, 1107–187 & 1504–166, common to both, Table 3.1), where the H I 21-cm or OH 18-cm transition fell into an available receiver band. These targets were originally intended to form part of the sample of Curran et al. (2006) and, as such, our targets are largely from the Parkes Half-Jansky Flat-spectrum Sample (PHFS, Drinkwater et al. 1997). These are bright and generally compact radio sources for which there exists comprehensive optical photometry (Francis et al. 2000). From a list of sources, for which the redshifted H I and OH frequencies fell into the available bands, we targeted a specific sub-sample for each telescope:

(i) For the Effelsberg telescope, our targets were selected on the basis of their having a “type-2” spectrum, with narrow emission lines, a red continuum and only weak (if any) broad emission line components. For these, unified schemes of AGN imply that our line-of-sight to the nucleus is blocked by a “dusty torus” (which obscures the broad line region and only allows us to view the narrow emission lines directly), through which we may expect to detect absorption. We therefore selected three radio galaxies (0114+074, 0454+066 & 1555–140¹) which exhibit optical spectra with narrow emission lines only, indicating the presence of some nuclear extinction. However, as since shown by Curran et al. (2008); Curran & Whiting (2010), AGN type has little bearing on whether absorption is detected (see Sect. 4.1).

(ii) For the Green Bank Telescope, as per Curran et al. (2006), the targets were selected on the basis of their flat radio spectra and very red optical-near-infrared colours, properties similar to the (then four, now five) objects with redshifted rotational absorption. Both 0108+388 and 0500+019 have been taken from Carilli et al. (1998), and so are known to exhibit associated H I absorption. The remainder were selected from the PHFS, on the basis of their optical-near-IR photometry (Francis et al. 2000), in which we selected the reddest objects in the sample, the colours of which are believed to be due to dust (Webster et al. 1995).

In this paper we present the results of 14 searches for associated H I absorption and 15 searches for OH. This is in addition to the 7 H I and 14 OH searched, using the Australia Telescope Compact Array and Giant Metre-Wave Radio Telescope (GMRT), by Curran et al. (2006) [with 3 H I and 5 OH searches overlapping with the present paper] and the 11 H I and 7 OH high redshift ($z \geq 2.9$) sources searched by Curran et al. (2008) [with no overlaps].

2.2 Effelsberg observations

The Effelsberg observations were performed with the 100-metre telescope from 9–12 May 2004. We used the UHF and 21/18-cm receivers over various bandwidths (in order to cover as wide a redshift range is possible, while minimising RFI) over 512 channels. System temperatures were typically $\lesssim 30$ K (when RFI was absent). Regarding each individual source:

4C+06.21 (0454+066) was observed at a central frequency of 1185.35 MHz over a 6 MHz bandwidth, giving a channel spacing

¹ One of the proposed targets, but not observed during this run. We have, however, since detected 21-cm absorption in this with the Australia Telescope Compact Array (Curran et al. 2006).

of 3.1 km s^{-1} . Although RFI was appreciable, an r.m.s. noise level of 67 mK was achieved over the 3.7 hour observation, although the flux density of the source could not be determined.

[HB89] 0114+074 was observed at a central frequency of 1058.43 MHz over a 6 MHz bandwidth, giving a channel spacing of 3.5 km s^{-1} . RFI was severe, dominating the 3.5 hour observation.

PKS 1107–187 was observed at a central frequency of 1112.51 MHz over a 12 MHz bandwidth, giving a spacing of 6.6 km s^{-1} . Unfortunately, RFI dominated the one hour observation.

Not on the original Effelsberg target list, due to severe RFI close to 887.76 MHz when observed at Green Bank, OH was searched for in **[HB89] 1504–166** over a 12 MHz bandwidth (giving a spacing of 8.2 km s^{-1}). Again, however, RFI was severe, allowing nothing to be salvaged from the 5.4 hour observation.

Due to the severe RFI we were encountering at $\lesssim 1.26 \text{ GHz}$, with the remaining time we selected a lower redshift target, **COINS J2355+4950 (2352+495)** [in which 21-cm is detected by Vermeulen et al. 2003], where OH would be redshifted to 1345.62 MHz. We observed over a 100 MHz bandwidth, giving a channel spacing of 43.5 km s^{-1} , and RFI was relatively low, allowing us to observe the source for 3.8 hours. This gave an r.m.s. noise level of 49 mK and a flux density equivalent to 3.504 K .²

The data were reduced using the GILDAS and XS packages.

2.3 Green Bank observations

Each of the sources targetted with the Green Bank Telescope were observed for a total of three hours with the observations being completed over several sessions in 2004, 2008 and 2009.³ For all observations, the Prime Focus 1 (PF1) receiver was used backed by the GBT spectrometer, with a 50 MHz band over 8 196 lags giving a channel spacing of 6.104 kHz (and the velocity spacings listed in Table 3.1). Two separate IFs were employed in order to observe both the H I and OH lines simultaneously:

COINS J0111+3906 (0108+388) was observed at 851.38 (H I) and 998.85 (OH) MHz on 7 September 2004. Both bands were RFI free over most of the band and system temperatures were $\leq 30 \text{ K}$. Minimal flagging was required, giving 2.1 hours of total integration at 851 MHz and 1.8 hours at 999 MHz.

4C-00.11 (0131–001) was observed at 765.01 MHz (H I) and 868.87 MHz (in order to also cover the 1612 and 1720 MHz OH satellite lines) in three sessions over 17 July to 31 August 2008. System temperatures were ≤ 40 and $\leq 30 \text{ K}$, respectively, although RFI was bad in the lower band. After flagging, 0.9 and 1.1 hours of data remained in the H I and OH bands, respectively.

4C-02.09 (0213–026) was observed for a total of two hours at 652.16 MHz (H I) on 31 October 2009. The system temperature was $\approx 80 \text{ K}$ and RFI caused around one half of the data to be completely flagged out. Of the remaining data, only 4 MHz of the 12.5 MHz wide band used was relatively RFI free, a range which fortunately covered the frequency expected for the 21-cm transition (Fig. 1 & Table 3.1). The OH line was searched at 765.65 MHz on 17 September 2009 for two hours over our standard 50 MHz bandwidth. The system temperature was 37 K and a clean band required minimal flagging leaving 1.7 hours of data.

PKS 0500+019 was observed at 1051.69 MHz only, since H I absorption is already detected (Carilli et al. 1998), on 2 October 2008. The system temperature was 24 K and RFI required some flagging, leaving one hour of data, although there remain intermittent dips across the band.

PKS 1107–187 was observed at 949.89 and 1113.16 MHz on 31 January 2009. System temperatures were 28 and 22 K, respectively, with only scans with wobbly band-passes and intermittent RFI spikes requiring removal in the lower band, leaving 1.7 hours of good data. We found an absorption feature close to 954 MHz, although this is twice as strong in one polarisation (see Sect. 3.2.2) and thus requires confirmation. The higher band was completely clean until the last half of the observation, when RFI spikes started moving across the band, leaving 1.0 hours of good data.

PKS 1430–155 was observed at 552.04 and 647.26 MHz on 15 February 2009. System temperatures were 86 and 43 K, respectively, where RFI was severe in both bands, although 8 minutes of good data could be retrieved at the higher frequency.

[HB89] 1504–166 was observed at 757.15 and 888.78 MHz on 30 April 2009. The system temperatures in the H I band was 40 K, with 0.7 hours of good data being retained. The OH band was completely wiped out by RFI.

PKS 1535+004 was observed at 315.84 and 370.46 on 25 October 2004. System temperatures were 87 and 76 K, respectively, and severe RFI meant that both bands had to be flagged extensively, leaving 1.2 hours of still relatively poor data.

4C-01.39 (1654–020) was observed at 475.01 and 557.23 MHz on 6 and 10 October 2008. The lower band had a system temperature of 40 K, although it was dominated by RFI. For the upper band, the system temperature was 115 K, but less severe RFI meant that 1.3 hours of data could be retained.

PKS 1706+006 was first observed on 7th September 2004 with frequencies centred on 980.27 and 1150.03 MHz where system temperatures were 30 and 24 K, respectively, with extensive flagging leaving 1 hour of data. Nevertheless, RFI dominated the higher frequency and so this was re-observed on 30 May 2009. Minimal flagging was required for these observations, although each scan exhibited a negative flux in each polarisation.

PKS 2252–089 was searched in H I on 16 July 2009 with a band centred on 844.22 MHz with a spacing of 3.052 kHz. The system temperature was 26 K, with very little flagging of bad data required. Since the OH band (centred on 1036.73 MHz) required the PF2 receiver, this was observed separately for one hour on both 5 June and 29 September 2009, at a spacing of 6.104 kHz, the system temperature being 25 K for both observations. On each occasion, although no time dependent flagging was required, the effect of RFI meant only the band shown in Fig. 1 was clean.

The data were reduced using the GBTIDL software.

2.4 Other data

In addition to the Effelsberg and GBT observations, we include the unpublished results of searches of other similar sources from Giant Metre-Wave Radio Telescope archival data:

- “Cold gas at high redshift” (PI: Braun, 02RbA01, 03RbA01), which yielded good data for H I and OH in 4C+41.17 and TXS 1243+036:

4C+41.17 (B3 0647+415) – for the H I observations, there were 20 hours of good data from a total of 4 observations (between August 2002 and February 2003) over 330 to 427 good baseline pairs. The OH band was searched on several occasions, but only the observa-

² The Effelsberg telescope has a sensitivity of 1.55 K per Jy in the UHF-band and 1.50 K per Jy in the 21/18-cm band.

³ Originally intended to be completed in 2004, thus being added to the sample of Curran et al. (2006) [Sect. 2.1].

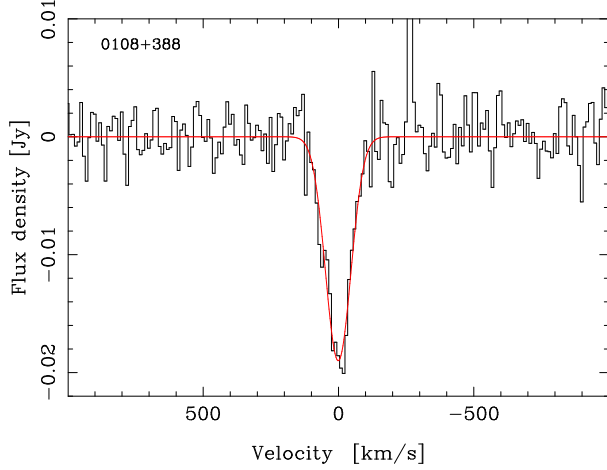


Figure 2. Single Gaussian fit to the H I absorption in 0108+388 shown at a resolution of 10 km s^{-1} . The velocity scale is relative to 851.32 MHz

tion of 3 February 2003 gave reasonable data, of which 6.4 hours over 401 baselines were good.

TXS 1243+036 (4C+03.24) – the H I band was observed over several runs, but only that from 30 August 2003 proves useful, with 2.3 hours of good data over 392 baseline pairs being retained. The several OH band observations also yielded only one good run (1 September 2002), of which 5.8 hours over 405 baseline pairs were retained.

- “H I absorption and emission in radio galaxies at $z \approx 0.4$ ” (PI: Blake, 05CBa01): Only one of the five sources searched yielded good data and a detectable flux, **4C+37.25 (B20847+37)**. This was observed on 17 April 2004, with 4.82 hours over 434 baseline pairs.

All of the GMRT data were reduced using the MIRIAD interferometry reduction package, with a spectrum extracted from each cube.

3 RESULTS

3.1 Observational results

In Fig. 1 we show the final spectra and summarise these in Table 3.1, where the optical depth limits are quoted per 10 km s^{-1} channel, apart from the low resolution observation of 2352+495, which is quoted per observed channel. We have detected H I in two (possibly three) of the targets (one of which is a re-detection) and do not detect OH in any.

3.2 H I detections

3.2.1 0108+388

In Fig. 2 we show the spectrum of the H I 21-cm absorption profile in 0108+388, which was previously detected by Carilli et al. (1998). The fitting of a single Gaussian to the profile gives a peak depth of $18.8 \pm 0.7 \text{ mJy}$ ($\approx 73 \text{ mJy}$ by Carilli et al. 1998) and a FWHM of $112 \pm 4 \text{ km s}^{-1}$ (cf. $94 \pm 10 \text{ km s}^{-1}$) at an observed frequency of $851.326 \pm 0.004 \text{ MHz}$ (giving a redshift $z = 0.66846 - 0.66847$ for the peak of the line). The previous observations were performed with the WSRT, giving a flux density of 180 mJy (cf. our 302 mJy). We use this previously imaged, more resolved, emission to derive an optical depth of $\tau = 0.10$, which, integrated over the FWHM of the profile, gives a column density of

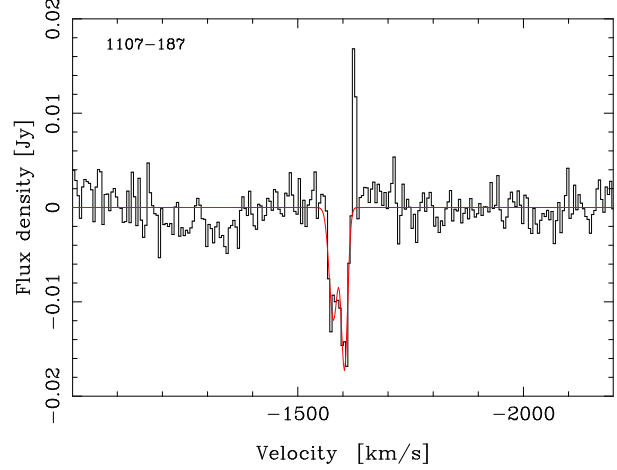


Figure 3. Two Gaussian fit to the possible H I absorption towards 1107–187 shown at a resolution of 5 km s^{-1} . The velocity scale is relative to 948.83 MHz and the fits give a 17 mJy deep feature at $z = 0.48905$ with a FWHM = 16 km s^{-1} and a 12 mJy deep feature at $z = 0.48917$ with a FWHM = 22 km s^{-1} .

$N_{\text{HI}} = 2.3 \pm 0.2 \times 10^{19} \cdot (T_s/f) \text{ cm}^{-2}$, where T_s is the spin temperature of the 21-cm transition and f is the covering factor. This column density is only 30% of the value obtained by Carilli et al. (1998) [$8.1 \pm 0.2 \times 10^{19} \cdot (T_s/f) \text{ cm}^{-2}$], which we believe is due to their lower quality spectrum.⁴

3.2.2 1107–187

We also report a possible 21-cm detection in 1107–187. This is apparent in both polarisations, although with quite different depths – $19.7 \pm 4.5 \text{ mJy}$ (at $953.86 \pm 0.01 \text{ MHz}$ with FWHM = $34 \pm 9 \text{ km s}^{-1}$) in the XX polarisation and $9.3 \pm 3.1 \text{ mJy}$ (at $953.87 \pm 0.02 \text{ MHz}$ with FWHM = $44 \pm 18 \text{ km s}^{-1}$) in the YY polarisation. The average of the two polarisations, with a single Gaussian fit, gives a line depth of $14.4 \pm 1.8 \text{ mJy}$ with a profile width of $50 \pm 11 \text{ km s}^{-1}$ (Fig. 3), the resulting optical depth of $\tau = 0.016 \pm 0.002$, giving $N_{\text{HI}} = 1.5 \pm 0.5 \times 10^{18} \cdot (T_s/f) \text{ cm}^{-2}$. The fit is centred on $953.87 \pm 0.01 \text{ MHz}$, giving a redshift of $z = 0.48909 \pm 0.00002$, cf. 0.497 quoted in the PHFS (Drinkwater et al. 1997). This suggests that the absorption may be blue-shifted by $\approx 1600 \text{ km s}^{-1}$ with respect to the galaxy, although the host redshift is known to only three significant figures. Note that of the many features apparent in the OH spectrum (Fig. 1), none give a ${}^2\Pi_{3/2}J = 3/2$ $F = 1 - 1$ (1665 MHz) — $F = 2 - 2$ (1667 MHz) pair with the same redshift as the 21-cm line.

3.2.3 2252–090

Finally, we report a new detection of 21-cm absorption in 2252–090, which was so strong as to be apparent in each 5 minute scan. This appears to be comprised of two major components (Fig. 4), one which is narrow and deep ($\tau = 0.129 \pm 0.007$, FWHM = $17 \pm 1 \text{ km s}^{-1}$, with $\nu = 883.578 \pm 0.001 \text{ MHz}$ giving $z =$

⁴ $N_{\text{HI}} = 8.1 \pm 0.2 \times 10^{19} \cdot (T_s/f) \text{ cm}^{-2}$ is the value derived using a Gaussian fit, whereas summing the actual channels over which the absorption occurs gives $8.0 \pm 2.2 \times 10^{19} \cdot (T_s/f) \text{ cm}^{-2}$. Applying this summing to our profile gives $2.2 \pm 0.2 \times 10^{19} \cdot (T_s/f) \text{ cm}^{-2}$, i.e. the same as the Gaussian fit.

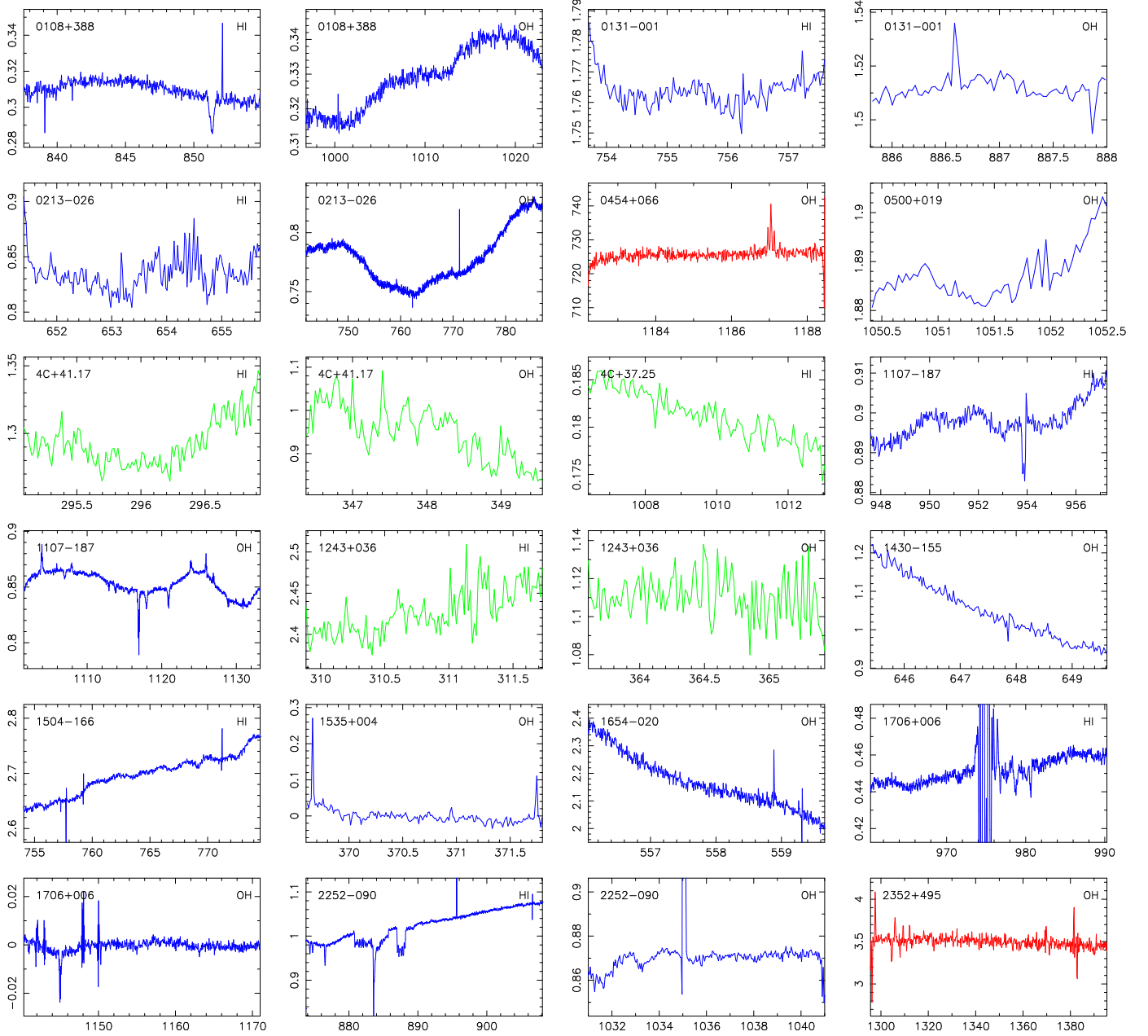


Figure 1. The useable spectra before baseline removal. The GBT (in blue) and GMRT (in green) spectra have the ordinate in flux density [Jy] and are shown over the RFI-free ranges (as quoted in Table 2) and the Effelsberg spectra (in red) have the ordinate in antenna temperature T_A^* [K] and are shown over the whole observed band. The abscissa the barycentric frequency [MHz]. Each is shown at a resolution of 10 km s^{-1} (except for 1654-020 shown at the observed 3.3 km s^{-1} and 2352+495 at 44 km s^{-1}). The 1535+004 and 1706+006 OH spectra after baseline removal are shown (Sect. 2.3). Note that the flux density for 4C+37.25, which is resolved, is over the central beam only.

0.60756), as well as a shallow, wide blue-shifted tail ($\tau = 0.076 \pm 0.003$, $\text{FWHM} = 94 \pm 5 \text{ km s}^{-1}$, with $\nu = 883.664 \pm 0.008 \text{ MHz}$ giving $z = 0.60741 \pm 0.00002$). A single Gaussian fit to the absorption gives $\tau = 0.12 \pm 0.01$ and $\text{FWHM} = 85 \pm 10 \text{ km s}^{-1}$ (centred on $\nu = 883.62 \pm 0.01 \text{ MHz} \Rightarrow z = 0.60748 \pm 0.00002$), with the velocity integrated optical depth giving $N_{\text{HI}} = 2.0 \pm 0.4 \times 10^{19} \cdot (T_s/f) \text{ cm}^{-2}$. This, along with 0108+338, is close to the maximum line strength detected in redshifted 21-cm (see Sect. 4.1, Fig. 5).

4 DISCUSSION

4.1 H I results

In Table 2 we summarise the line strengths/limits from these new searches for redshifted H I 21-cm and OH 18-cm absorption. For the 21-cm searches, we have obtained one, possibly two new detections, as well as confirming and improving upon a previous detection. From the top panel of Fig. 5, we see that all of the sources have been searched as deeply as in previous surveys and from the bottom panel, we see a range of 1216 \AA luminosities (given in Table 2): Curran et al. (2008) found a critical luminosity ($L_{\text{UV}} \sim 10^{23} \text{ W}$

Table 1 The targets searched and the observational results. These are named according to the IAU B1950 positions (the full names are given in Sect. 2). ν_{obs} is the observed frequency range of the line over which the quoted r.m.s. level is applicable [MHz], σ_{rms} is the r.m.s. noise [mJy] reached per $\Delta\nu$ channel [km s^{-1}] after subtraction of a low order baseline, S_{cont} is the continuum flux density [Jy], τ is the optical depth of the line calculated for a 10 km s^{-1} channel (except for 2352+495, see main text), where $\tau = -\ln(1 - 3\sigma_{\text{rms}}/S_{\text{cont}})$ is quoted for the non-detections. In all cases, OH refers to the ${}^2\Pi_{3/2}J = 3/2 \ F = 2 - 2$ (1667 MHz) transition. The final columns give the B , V , R & K magnitudes.

Source	z_{host}	Line	ν_{obs}	σ_{rms}	$\Delta\nu$	S_{cont}	τ	Tel.	B	Ref	V	Ref	R	Ref	K	Ref
0108+388	0.66847	H I	837.6–854.9	1.0 ^a	2.15	0.303	0.10	GBT	—	—	—	—	22.0	S93	16.69	S96
...	...	OH	996.8–1023.0	3.6 ^b	1.83	0.314	< 0.015	GBT	...	...	...	...	...	...	...	...
0114+074	0.342	H I	1058.2	—	RFI DOMINANT	—	—	Eff	20.658	H01	—	—	18.240	H01	15.390	FPC
0131–001	0.879	H I	753.7–757.6	3.7	2.42	1.76	< 0.0031	GBT	23.340	F00	22.500	F00	20.780	F00	16.780	F00
...	...	OH	885.8–888.0	5.1	2.06	1.51	< 0.0046	GBT	...	...	...	...	...	...	...	...
0213–026	1.178	H I	651.4–655.7	243	0.35	0.913	< 0.16	GBT	21.475	H01	20.820	F00	20.475	H01	15.050	S06
...	...	OH	742.6–786.6	5.2	2.40	0.756	< 0.010	GBT	...	...	...	...	...	...	...	...
0454+066	0.405	OH	1182.2–1188.4	45	3.09	0.55 ^c	< 0.15	Eff	19.514	H01	—	—	18.589	H01	15.035	S06
0500+019	0.58477	OH	1050.4–1052.5	11 ^d	0.87	1.89	< 0.0052	GBT	22.500	D97	21.350	C03	20.682	C03	15.430	FPC
0647+415	3.79786	H I	295.1–296.9	17	15.8	1.29	< 0.050	GMRT	—	—	—	—	21.700	C90	18.60	C90
...	...	OH	346.4–349.6	63	26.9	0.949	< 0.40	GMRT	...	...	...	...	...	...	...	...
0847+37	0.406818	H I	1005.8–1013.3	1.7	18.6	187	< 0.037	GMRT	20.804	SDR7	19.613	SDR7	18.895	SDR7	—	—
1107–187	0.497	H I	947.6–957.3	4.1	1.93	0.896	0.016 ^e	GBT	22.262	H01	21.100	F00	19.509	H01	15.950	F00
...	...	OH	1101.5–1133.2	5.4	1.65	0.853	< 0.0077	GBT	...	...	...	...	...	...	...	...
...	...	OH	1113.8	—	RFI DOMINANT ^f	—	—	Eff	...	...	...	...	...	...	...	...
1243+036	3.5699	H I	309.9–311.7	28	15.1	2.43	< 0.042	GMRT	23.076	SDR7	21.562	SDR7	20.665	SDR7	—	—
...	...	OH	363.6–365.4	12	12.8	1.11	< 0.037	GMRT	...	...	...	...	...	...	...	...
1430–155	1.573	H I	552.0	—	RFI DOMINANT	—	—	GBT	22.500	D97	23.240	F00	22.910	F00	17.500	F00
...	...	OH	645.4–649.6	24	2.83	1.03	< 0.037	GBT	...	...	...	...	...	...	...	...
1504–166	0.876	H I	754.1–774.6	52	2.42	2.62	< 0.012	GBT	19.050	D97	19.750	F00	19.350	F00	14.010	F00
...	...	OH	—	—	RFI DOMINANT	—	—	GBT	...	...	...	...	...	...	...	...
...	...	OH	887.8–894.0	—	RFI DOMINANT	—	—	Eff	...	...	...	...	...	...	...	...
1535+004	3.497	H I	315.8	—	RFI DOMINANT	—	—	GBT	—	—	—	—	—	—	19.540	FPC
...	...	OH	369.6–371.8	15 ^g	4.94	—	< 0.08	GBT	...	...	...	...	...	...	...	...
1654–020	1.99	H I	475.0	—	RFI DOMINANT	—	—	GBT	23.700	D97	23.900	F00	23.050	F00	18.250	F00
...	...	OH	556.1–559.7	18	3.28	2.20	< 0.014	GBT	...	...	...	...	...	...	...	...
1706+006	0.449	H I	960.4–990.3 ^h	5.2	1.87	0.453	< 0.015	GBT	22.000	H06	20.590	F00	20.350	H06	15.630	F00
...	...	OH	1140.3–1171.0	5.4	1.59	0.524 ⁱ	< 0.0010	GBT	...	...	...	...	...	...	...	...
2252–089	0.6064	H I	873.8–908.1	1.0	5.6 ^j	0.990	0.11	GBT	22.500	D97	21.510	F00	20.490	F00	16.480	F00
...	...	OH	1031.6–1040.5	2.9	1.77	0.871	< 0.0042	GBT	...	...	...	...	...	...	...	...
2352+495	0.23783	OH	1313.7–1380.4	32 ^k	43.5	2.25	< 0.043	Eff	21.101	H01	—	—	18.497	H01	15.112	S06

Photometry references: C90 – Chambers et al. (1990), O90 – O’Dea et al. (1990), S93 – Stanghellini et al. (1993), T93 – Tadhunter et al. (1993), S94 – Stickel & Kühr (1994), S96 – Stickel et al. (1996), D97 – Drinkwater et al. (1997), F00 – Francis et al. (2000), H01 – SuperCOSMOS Sky Survey (Hambly et al. 2001), C03 – Cody & Braun (2003), S06 – 2MASS (Skrutskie et al. 2006), SDR7 – SDSS DR7, A08 – Adelman-McCarthy et al. (2008), FPC – P. Francis (priv. comm.).

Notes: ^aDetected previously by Carilli et al. (1998) [Sect. 3.2.1], ^balso undetected at an r.m.s. of 2.9 mJy per 19 km s^{-1} channel with the GMRT (Curran et al. 2006), ^cderived using the a flux density of 0.55 Jy, estimated from the neighbouring 408 and 1400 MHz values (Douglas et al. 1996; Condon et al. 1998), ^dH I detected by Carilli et al. (1998), OH previously undetected at an r.m.s. of 7.4 mJy per 18 km s^{-1} channel with the GMRT (Curran et al. 2006), ^e $\tau < 0.0060$ if detection not real (Sect. 3.2.2), ^fOH previously undetected at an r.m.s. of 2.4 mJy per 17 km s^{-1} channel with the GMRT (Curran et al. 2006), ^gH I undetected at an r.m.s. of 7.3 mJy per 15 km s^{-1} channel with the GMRT (Curran et al. 2006) and optical depth calculated using $S_{365 \text{ MHz}} = 0.389 \text{ Jy}$ (Douglas et al. 1996), ^hneglecting the RFI at 973.5–977.6 MHz, ⁱfrom the 2004 observations, ^j15 mJy in vicinity of absorption feature (880.79–888.34 MHz), ^kH I detected by Vermeulen et al. (2003).

Table 2. The H I column densities, N , derived from the optical depths given in Table 3.1. T_s is the spin temperature of the H I 21-cm, T_x is the excitation temperature of the OH and f the respective covering factor. z -range is the redshift range over which the column density limit applies (Table 3.1), followed by the galaxy/quasar classification. The final columns give the AGN type and 1216Å luminosity [W Hz^{-1}], determined/calculated as per Curran et al. (2008).

Source	z_{host}	Line	$N [\text{cm}^{-2}]$	z -range	Class	Type	Ref	$\log L_{\text{UV}}$
0108+388	0.66847	H I	$2.3 \pm 0.2 \times 10^{19} \cdot (T_s/f)$	0.66847	Gal	2	L96	20.309
...	...	OH	$< 3.6 \times 10^{13} \cdot (T_x/f)$	0.62987–0.67268	...	...	...	...
0131–001	0.879	H I	$< 5.7 \times 10^{16} \cdot (T_s/f)$	0.87488–0.88458	QSO	–	–	20.221
...	...	OH	$< 1.1 \times 10^{13} \cdot (T_x/f)$	0.87766–0.88232	...	...	...	...
0213–026	1.178	H I	$< 2.9 \times 10^{18} \cdot (T_s/f)$	1.16624–1.18054	QSO	2	D97a	22.119
...	...	OH	$< 2.4 \times 10^{13} \cdot (T_x/f)$	1.11960–1.24545	...	...	...	...
0454+066	0.405	OH	$< 3.6 \times 10^{14} \cdot (T_x/f)$	0.40138–0.40873	QSO	2	D97a	21.567
0500+019	0.58477	OH	$< 1.2 \times 10^{13} \cdot (T_x/f)$	0.58419–0.58736	Gal	2	H03	20.367
0647+415	3.79786	H I	$< 9.1 \times 10^{17} \cdot (T_s/f)$	3.78364–3.81379	Gal	2	D97b	23.258
...	...	OH	$< 9.5 \times 10^{14} \cdot (T_x/f)$	3.76988–3.81423	...	...	...	...
0847+37	0.406818	H I	$< 6.8 \times 10^{17} \cdot (T_s/f)$	0.40183–0.41221	Gal	2	SDR7	20.930
1107–187	0.497	H I	$1.5 \pm 0.5 \times 10^{18} \cdot (T_s/f)^*$	0.48909	Gal	1	D97a	19.157
...	...	OH	$< 1.8 \times 10^{13} \cdot (T_x/f)$	0.47137–0.51372	...	...	...	...
1243+036	3.5699	H I	$< 7.7 \times 10^{17} \cdot (T_s/f)$	3.55653–3.58388	Gal	2	R97	23.382
...	...	OH	$< 8.8 \times 10^{13} \cdot (T_x/f)$	3.56273–3.58607	...	...	...	...
1430–155	1.573	OH	$< 8.8 \times 10^{13} \cdot (T_x/f)$	1.56667–1.58345	QSO	1	D97a	21.790
1504–166	0.876	H I	$< 2.2 \times 10^{17} \cdot (T_s/f)$	0.83385–0.88365	QSO	1	H78	22.361
1535+004	3.497	OH	$< 1.9 \times 10^{14} \cdot (T_x/f)$	3.48456–3.51125	QSO	—	—	—
1654–020	1.99	OH	$< 3.3 \times 10^{13} \cdot (T_x/f)$	1.97924–1.99858	Gal	1	D97a	22.151
1706+006	0.449	H I	$< 2.7 \times 10^{17} \cdot (T_s/f)$	0.43436–0.47902 [†]	Gal	2	D97a	19.838
...	...	OH	$< 2.5 \times 10^{13} \cdot (T_x/f)$	0.42388–0.46221	...	...	...	...
2252–090	0.6064	H I	$2.0 \pm 0.4 \times 10^{19} \cdot (T_s/f)$	0.60748	Gal	2	D97a	20.802
...	...	OH	$< 1.0 \times 10^{13} \cdot (T_x/f)$	0.60246–0.6162	...	...	...	...
2352+495	0.23783	OH	$< 1.0 \times 10^{13} \cdot (T_x/f)$	0.20788–0.26921	Gal	2	L96	19.030

Notes: * $N_{\text{HI}} < 1.1 \times 10^{17} \cdot (T_s/f) \text{ cm}^{-2}$ at $z = 0.48381 - 0.49898$ over the absorption free region if a false detection,

[†] with RFI at $z = 0.453 - 0.459$.

References: H78 – Hunstead et al. (1978), L96 – Lawrence et al. (1996), D97a – Drinkwater et al. (1997), D97b – Dey et al. (1997), R97 – Roettgering et al. (1997), H03 – Hook et al. (2003), SDR7 – SDSS DR7.

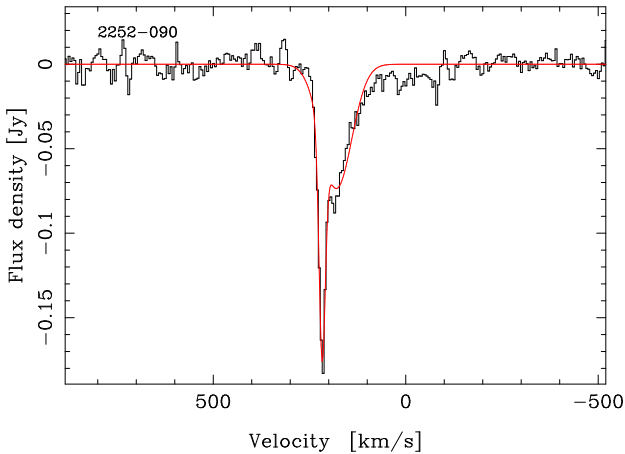


Figure 4. Two Gaussian fit to the H I absorption in 2252–090 shown at a resolution of 5 km s^{-1} . The velocity scale is relative to 884.22 MHz

Hz^{-1}) at this wavelength, above which 21-cm has never been detected. All but two of the sample lie below this threshold, these being 0647+415 and 1243+036 (Sect. 2.4), which, as our previous $z \sim 3 - 4$ searches (Curran et al. 2008), are above the critical luminosity due to their high redshifts causing the selection of the brightest sources, despite their relatively faint magnitudes (Table 3.1, cf. figure 5 of Curran et al. 2010b). These two new high redshift sources differ from all of the other $L_{\text{UV}} \gtrsim 10^{23} \text{ W Hz}^{-1}$

targets searched in 21-cm in that they are type-2 objects. Their inclusion increases the significance of the ultra-violet luminosity effect, with the binomial probability of 0 out of 19 detections occurring by chance being just 1.9×10^{-6} , if a 21-cm detection and non-detection are equally probable. Assuming Gaussian statistics, this corresponds to a significance of 4.76σ .

As mentioned in Sect. 2.1, the distribution of 21-cm detections in radio galaxies and quasars is usually attributed to unified schemes of active galactic nuclei (Antonucci 1993; Urry & Padovani 1995), where, due to the edge-on torus of dense circumnuclear material, type-2 objects (usually galaxies) present a thick column of intervening gas along our sight-line and thus absorb in 21-cm (Jaffe & McNamara 1994; Conway & Blanco 1995), whereas type-1 objects (usually quasars) do not. Of the new detections, one is type-2 and one is type-1 (assuming that 1107–187 is a detection, Sect. 3.2.2), and contributing to a type-2 detection rate of 46% and a type-1 rate of 48%, these confirm our previous finding that unified schemes of AGN cannot be used to explain the incidence of 21-cm absorption in these objects (cf. Morganti et al. 2001; Pihlström et al. 2003; Gupta et al. 2006; Gupta & Saikia 2006). That is, these results further support our suggestion the bulk of the cool gas is located in the main galactic disk, which is randomly oriented with respect to the torus of obscuring material invoked by unified schemes of AGN (Curran & Whiting 2010).

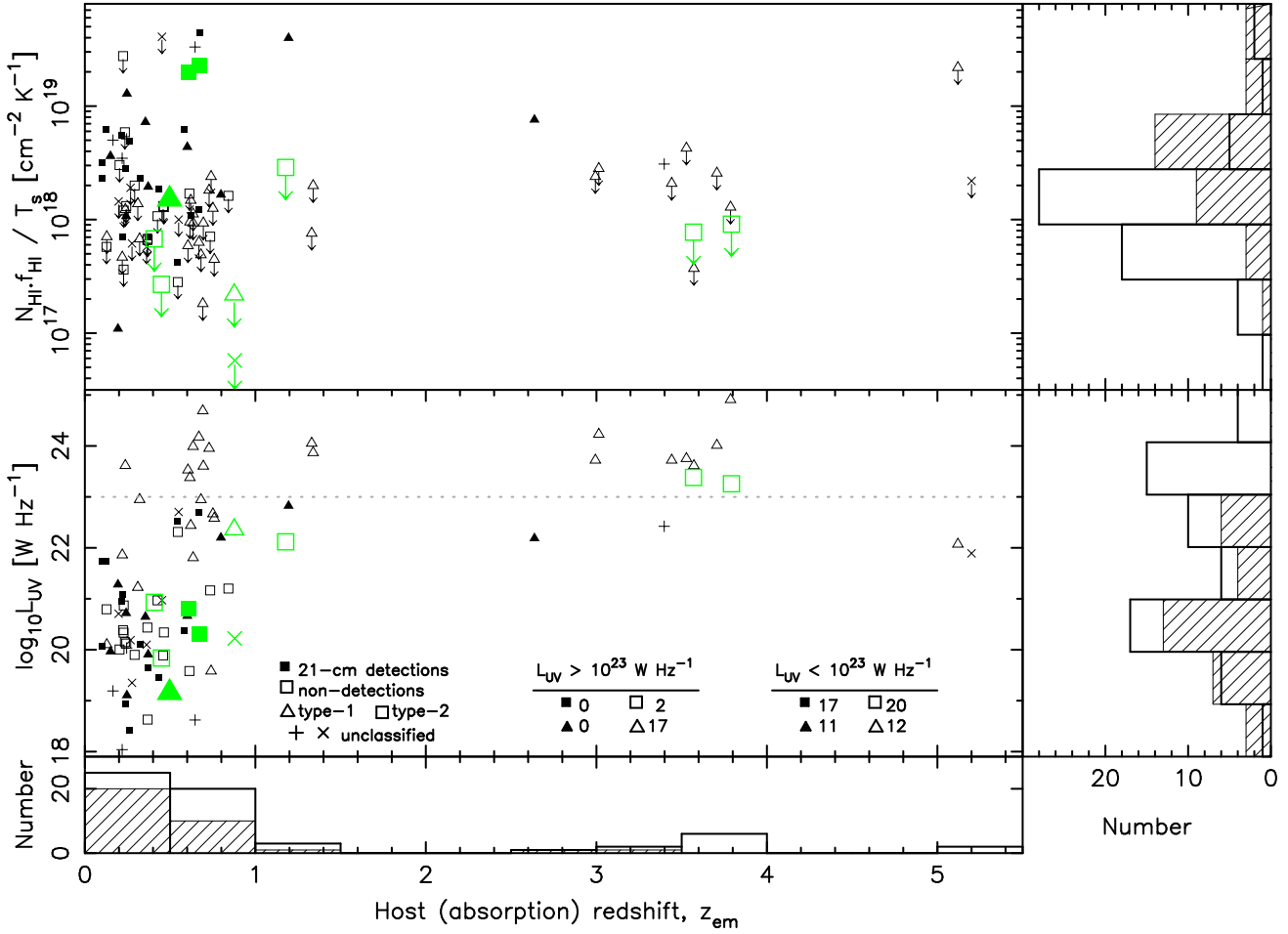


Figure 5. The scaled velocity integrated optical depth of the H I line ($1.823 \times 10^{18} \cdot \int \tau dv$) [top] and the ultra-violet ($\lambda \approx 1216 \text{ \AA}$) luminosity [bottom] versus the host redshift for the $z \geq 0.1$ radio galaxies and quasars searched in associated 21-cm absorption. The filled symbols/hatched histogram represent the 21-cm detections and the unfilled symbols/unfilled histogram the non-detections, with the large coloured symbols designating the new results presented here (1107–187 is treated as a detection, Sect. 3.2.2). The shapes represent the AGN classifications, with triangles representing type-1 objects and squares type-2s (+ and x designate an undetermined AGN type for a detection and non-detection, respectively). The legend shows the number of each AGN type according to the $L_{\text{UV}} = 10^{23} \text{ W Hz}^{-1}$ partition.

4.2 OH results

Although OH was not detected in any of the sample, from the H I detections⁵ we can obtain normalised OH line strength limits in order to compare with the five detected OH absorbers. In Fig. 6 we add the new results to the molecular line strength/optical-near-IR colour correlation found by Curran et al. (2006), showing also the corresponding distributions using the blue and red magnitudes. Since the full-width half maxima (FWHM) of the OH lines are expected to be close to those of the 21-cm profiles (Curran et al. 2007), as per Curran et al. (2008), we have rescaled the OH column densities limits by $\sqrt{\text{FWHM}_{\text{HI}}/\Delta v}$, in order to give the limit of a single channel “smoothed” to $\text{FWHM}_{\text{OH}} \approx \text{FWHM}_{\text{HI}}$. This should give a more accurate estimate of the upper limit than quoting this per Δv channel.⁶

From this, we see that, even if the reddening of the quasar light

does occur within its host galaxy and not at some intervening redshift, according to the five known OH absorbers, only 0500+019 and (from the $R-K$ plot) 0108+388 may have been searched sufficiently deeply. Although the limit is close to the expected detection threshold, 0500+019 is also undetected in HCO^+ , to limits which are significantly stronger according to the $N_{\text{HCO}^+}-V-K$ correlation (Curran et al. 2010a), and so perhaps the reddening of this source does not occur in the host galaxy but is the cause of some intervening absorber.⁷

Note finally, that the addition of these limits through the ASURV survival analysis package (Isobe et al. 1986), increases the significance of the $V-K$ correlation over that for the OH detections only ($S(\tau) = 1.96\sigma$, Curran et al. 2006). For the $B-K$ and $R-K$ correlations the significance is somewhat lower, although, due to the limited availability of these magnitudes for the known

⁵ 0108+388, 0500+019, 1107–187, 2352+495 (this paper), 0902+343 (Cody & Braun 2003), J1124+1919, J1347+1217 and J2316+0404 (Gupta et al. 2006).

⁶ Δv is the original resolution of the observations or the 10 km s^{-1} used in Table 3.1 and FWHM_{HI} is obtained from Mirabel (1989); Carilli et al.

(1998); Cody & Braun (2003); Vermeulen et al. (2003); Gupta et al. (2006), as well as this paper (Sect. 3.2).

⁷ $< 30\%$ of the redshift space towards 0500+019 has been scanned for HCO^+ (Murphy et al. 2003), although the detection of OH does not ensure the detection of a millimetre transition (Kanevar et al. 2005).

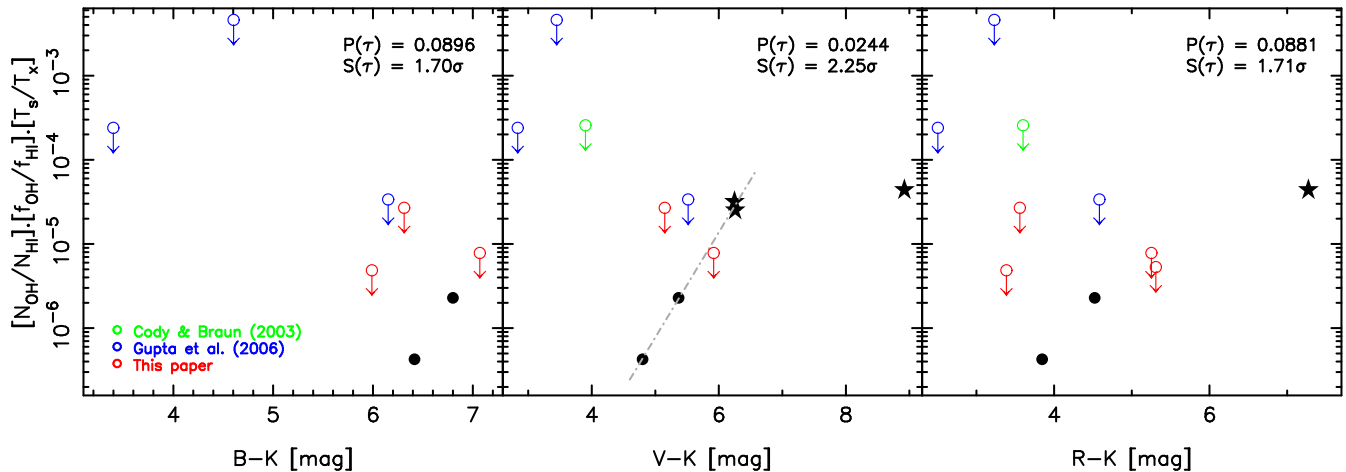


Figure 6. The normalised OH ${}^2\Pi_{3/2}J = 3/2$ (1667 MHz) line strength ($2.38 \times 10^{14} \int \tau_{\text{OH}} dv / 1.82 \times 10^{18} \int \tau_{\text{HI}} dv$) versus the blue–near-IR (left), optical–near-IR (middle) and red–near-IR (right) colour. The filled symbols show the five known OH absorbers (circles – associated, stars – intervening absorbers, see Curran et al. 2006 and references therein) and the unfilled symbols the H I 21-cm detections with OH upper limits, colour coded by reference (green – Cody & Braun 2003, blue – Gupta et al. (2006) and red – this paper). The probability of each distribution occurring by chance is shown, along with the associated significance (see main text). The line shows the least-squares fit to those also detected in millimetre-band molecular transitions for the optical–near-IR colours (Curran et al. 2006).

absorbers, this is not surprising being based upon only two or three detections.

5 SUMMARY

We have undertaken a survey for redshifted H I 21-cm and OH 18-cm absorption in a sample of type-2 AGN and reddened flat spectrum objects with the Effelsberg and Green Bank telescopes. We also include unpublished searches of similar objects with the Giant Metre-Wave Radio Telescope. Of the ten objects for which there are useful data, we report one new clear 21-cm detection, in addition to a possible detection, and confirm and significantly improve upon a previous detection (all with the GBT). The selection criteria for the targets pre-date the findings of Curran et al. (2008), although they confirm these:

(i) All of the 21-cm detections occur in objects with $\lambda = 1216 \text{ \AA}$ luminosities of $L_{\text{UV}} \leq 10^{23} \text{ W Hz}^{-1}$, a range within which there are also four new non-detections. All of the detections arise in galaxies (as opposed to quasars), which have been noted to have higher 21-cm detection rates (52% for galaxies compared to 17% for quasars), this being attributed to galaxies tending to be type-2 objects. However, Curran & Whiting (2010) have shown that the higher detection rate in galaxies is likely to be a consequence of their generally lower UV luminosities, as opposed to their AGN classification.

(ii) The two objects for which $L_{\text{UV}} > 10^{23} \text{ W Hz}^{-1}$ are undetected, confirming that the ultra-violet luminosity is an important criterion in the detection of cool neutral gas (Curran & Whiting 2010). Their inclusion, the first published type-2 $L_{\text{UV}} > 10^{23} \text{ W Hz}^{-1}$ sources searched for in 21-cm, raises the significance of the UV luminosity–21-cm anti-correlation to 4.76σ .

(iii) At $L_{\text{UV}} \leq 10^{23} \text{ W Hz}^{-1}$, the detection rates for both type-1 and type-2 objects remain close to 50%, supporting the hypothesis that unified schemes of active galactic nuclei cannot account for the observed incidence of 21-cm absorption in radio galaxies and quasars.

Fourteen of the sources searched in OH had useful data, although only two of these have 21-cm detections, thus being able to yield limits on the normalised line strengths. Adding those from the literature, gives a total of eight objects for which we can normalise the line strengths and thus compare with the five known OH absorbers. On this basis, however, we find that only two (0108+388 & 0500+019, both from this paper) come close to having been searched deeply enough. This confirms the findings of Curran et al. (2006) that many of the known objects are simply not “red enough” to indicate sufficiently large columns of dust, conducive to the presence of molecular gas, along their sight-lines.

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